Measuring the Interplanetary Medium with a Solar Sail

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Abstract

NASA has been considering a solar sail that would accelerate a craft to a high velocity ($\sim$14 AU/yr) by the time it reached 5 AU. Then the sail would be dropped and the craft would coast alone to deep space. We propose that the sail be retained longer. Then the density of the interplanetary medium could be determined by measuring the drag force on the huge sail using radiometric navigational data. Such an experiment would yield an independent, new type of measurement of the interplanetary medium and should be pursued.

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1 Introduction

Sending a spacecraft beyond the heliopause to begin the exploration of our local galactic neighborhood will be one of the grand scientific enterprises of this century. NASA's InterStellar Probe [1]-[4], for example, could be the first spacecraft that investigates the nearby interstellar medium and its interaction with our solar system. We point out here that the sail could also be used for an independent determination of the interplanetary medium by measuring the drag force on it as it passed through the solar system.

The space between the planets in our solar system is far from empty. We know that the interplanetary medium has the following structure: First there is the electromagnetic part, composed of the (i) solar radiation (photons) and (ii) the magnetic field (also primarily originating at the Sun). The material components of the interplanetary medium consist of thinly scattered matter in the form of (iii) neutral hydrogen and microscopic dust particles and (iv) a hot plasma of electrically charged particles (chiefly protons and electrons produced by ionization), a.k.a. the solar wind.

While the Sun's radiation is obvious, the other components of the interplanetary medium were not directly discovered until the era of modern space exploration. The exact composition of the material content is still being debated and many models as to what what exactly is its nature and origin have been proposed. Whatever the total picture, it is the Kuiper belt that is the most significant.

In 1951 Kuiper suggested that some comet-like debris from the formation of the solar system must exist beyond Neptune. This since-discovered "Kuiper Belt" is a disk-shaped region past the orbit of Neptune, roughly 30 to 100 AU from the Sun, containing dust and many small icy bodies. It is now considered to be the source of the short-period comets. (The long-period comets are believed to be formed further away in the Oort cloud.)

There currently is great interest in understanding the Kuiper belt region. In particular, the study of the trans-Neptunian asteroids is a rapidly evolving field of research,

with major observational and theoretical advances in the last few years. Further interest in the Kuiper belt comes from disk-shaped regions of dust having been observed around other stars in several systems.

The currently envisioned missions to the edge of the solar system will, of course, travel through the Kuiper belt. For a solar sail mission, the sail is first be used to bring the spacecraft in to 0.25 AU. Then, as the craft is rotated to be directly "upwind" it is subjected to a large outward radiation pressure that initiates its journey to the interstellar region.

The standard concept is to jettison the sail at approximately 5 AU, when the craft is already near its terminal velocity (see Section 3), thereby avoiding any later complications with the sail. The spacecraft then coasts, hopefully staying alive until it reaches 200 – 400 AU. It would explore the Kuiper belt, the boundaries of the heliosphere, and the nearby interstellar medium. Solar sail propulsion was selected for this mission because of recent dramatic advances in solar sail materials development.

However, if the sail were *not* jettisoned at 5 AU, but kept, if would provide an excellent opportunity to "directly" measure the density of matter (dust and gas) in the Kuiper belt by observing the drag produced on the sail. Here we will analyze the potential application of a solar sail for detecting the properties of the interplanetary medium.

We will examine whether interplanetary matter, such as that in the Kuiper belt would produce a measurable drag on a solar sail. We find that a solar sail mission might be extremely useful in directly determining the amount of dust and gas in the deep solar system. Indeed, we show that a modest navigation effort (much less than the state of the art) will determine the orbital parameters of the sail to the needed accuracy. Therefore, this novel space travel technology would offer a unique instrument to study the dust and particle content in the distant regions of our solar system, at little additional cost to a planned primary mission.

2 Major Forces on the Sail

For definiteness in our analysis we will consider a project with the characteristics of the InterStellar Probe Mission [1]-[4]. In the mission concept developed by NASA's InterStellar Probe Science and Technology Definition Team, a 400-m diameter solar sail accelerates the spacecraft to ~ 14 AU/year (1 AU/yr = 4.74 km/s). It has a total cruising mass of $m \sim 300$ kg, the radius of the sail is ~ 200 m, and the radius of the inside craft mount ~ 5.5 m. As noted above, the sail is nominally to be abandoned at 5 AU. when the craft has a velocity near its hyperbolic terminal velocity of $v_s(\infty) \sim 14.1$ AU/year.[1]

InterStellar Probe's unique voyage from Earth to beyond 200 AU will enable the first comprehensive measurements of the plasma, neutrals, dust, magnetic fields, energetic particles, cosmic rays, and infrared emission in the outer solar system out to the boundary of the heliosphere and beyond into the interstellar medium. This will allow the mission to address key questions about the distribution of matter in the outer solar system, the processes by which the Sun interacts with the galaxy, and the nature and properties of the nearby galactic medium.

However, if, as proposed in the introduction, the solar sail was retained through the inner regions of our solar system, such a mission could also yield very important results on the dust and particle content on the way to interstellar space.

We now consider this particular trajectory phase of the mission, when the craft is still within the solar system. The major forces on the craft and sail in this period are gravity and solar radiation pressure. (There is also a very small force due to the solar wind.) Below we shall discuss the effect of these forces in detail. In the next section we will discuss the drag force, whose measurement is what we are proposing.

[1] There are also other interesting concepts, such as the ESA/German Odissee concept [5].

Gravitational acceleration: The Newtonian gravitation acceleration is simple to compute and it is given by

$$a_{\tt G} = -\frac{G\ M_\odot}{r^2} = -0.594\Big[\frac{1\ \mathrm{AU}}{r}\Big]^2\ \ \mathrm{cm/s^2}. \tag{1}$$

The effects of Jupiter and the other planets, as well as general relativistic effects, are included in all standard Orbital Determination Programs. We ignore them here since we are concentrating on the relative sizes of non-inertial forces with respect to gravitational forces and to navigational precision.

Solar radiation pressure: The acceleration due to solar radiation pressure is also well-known and is given by

$$a_{\tt sr} = \mathcal{K}_{\tt sr}\ \frac{f_\odot\ A}{c\ m\ \ r^2}, \tag{2}$$

where $\mathcal{K}_{\tt sr}$ is the effective reflection/absorption/transmission coefficient of the sail, $f_\odot =$ 1367 W/m^2(AU)^2 is the "solar radiation constant" at 1 AU from the Sun, A is the effective area of the craft as seen by the Sun, c is the speed of light, and m is the mass of the craft. Designs call for most of the solar radiation being reflected and the rest transmitted [1]. Therefore, given the properties of the proposed sail materials, $\mathcal{K}_{\tt sr}$ might be in the neighborhood of 1.6-1.8, but we leave it as a parameter. (Total reflection would have a $\mathcal{K}_{\tt sr} = 2$, total absorption would yield 1, and total transmission would give 0.)

Putting in the numbers we have

$$a_{\tt sr} = 0.191\ \mathcal{K}_{\tt sr}\ \Big[\frac{1\ \mathrm{AU}}{r}\Big]^2\ \ \mathrm{cm/s^2}. \tag{3}$$

So, the solar radiation acceleration is about one-third that of the Sun's gravity, but in the opposite direction.

Solar wind acceleration: The proton number density of the interplanetary plasma is about 5 protons/cm^3 $\rightarrow 0.8 \times 10^{-23}$ g/cm^3 near the Earth. This density decreases roughly as an inverse-square law farther from the Sun. However, the density is highly

variable, it can be as much as 100 protons/cm^3. Though very tenuous, it's properties can be measured by spacecraft. Near 1 AU the temperature of the interplanetary plasma is about 100,000 K, and its current velocity $v_{\tt sw}$ is on the order of 400 km/s.[2]

The acceleration caused by the solar wind has the same mathematical form as Eq. (2), with $f_\odot/c$ replaced by $m_p v_{\tt sw}^2 n_p$, where m_p is the proton mass and $n_p \approx 5$ cm^{-3} is the proton number density at 1 AU. Thus, we have

$$\begin{aligned} a_{\tt sw}(r) &= \mathcal{K}_{\tt sw} \frac{m_p v_{\tt sw}^2\, n_p\, A}{m\, r^2} \\ &\approx 5.61 \times 10^{-5}\, \mathcal{K}_{\tt sw} \left[\frac{1 \text{ AU}}{r}\right]^2 \text{ cm/s}^2, \end{aligned} \tag{4}$$

where again $\mathcal{K}_{\tt sw}$ is an effective reflection/absorption/transmission coefficient for the sail. Therefore, the effect of the solar wind is much smaller than the effects of solar gravity or the solar radiation pressure.

3 Drag Forces on the Sail

Since any drag force depends on the relative velocity of the craft, let us first will review how the velocity of the craft will evolve in its mission.

The velocity of the craft in deep space: For a spacecraft in deep space, one can compute its velocity to first order using standard Newtonian mechanics. Given that $v_s(\infty) = 14.1$ AU/yr, the velocity between sail jettison time (foreseen to be at 5 AU) and infinity would approximately be (ignoring the angular momentum energy)

$$\begin{aligned} v_s(r) &\approx \left[v_s^2(\infty) + \frac{GM_\odot}{2r}\right]^{1/2} \\ &\approx \left[14.1 \; + \; \frac{0.7 \text{ AU}}{r} \; + \; \ldots\right] \text{ AU/yr}, \end{aligned} \tag{5}$$

meaning, specifically, that

$$v_s(r = 5 \text{ AU}) = 14.24 \text{ AU/yr} \approx 67.5 \text{ km/s}. \tag{6}$$

[2]The current "space weather" near the Earth can be found at [6].

This shows that after 5 AU, the slowing effect of gravity would not significantly affect the time of travel to deep space. Over time, gravity will decrease the hyperbolic velocity by only 0.14 AU/yr. If, on the other hand, the sail remained attached to the craft after 5 AU, comparing Eqs. (1) and (3) shows that the solar sail would contribute only about +0.05 AU/yr in terminal velocity. Therefore, to avoid possible measurement problems the sail ordinarily the sail would be abandoned at a distance of about 5 AU from the Sun.

The drag acceleration at 5 AU and beyond: Consider the drag force if the sail remained attached at and beyond 5 AU. The acceleration due to drag from the interplanetary medium is

$$a_{\mathtt{d}}(r) = -\mathcal{K}_{\mathtt{d}} \frac{\rho \;\; v_s^2(r)\, A}{m}, \tag{7}$$

where $\rho(r)$ is the density of the interplanetary medium, $\mathcal{K}_{\mathtt{d}}$ is the effective reflection/absorption/transmission coefficient of the sail for the particles being hit by the sail, and $v_s^2(r)$ is the effective relative velocity of the craft with respect to the medium. The critical unknowns are $\rho(r)$ and $\mathcal{K}_{\mathtt{d}}$.

Current limits on the gas and dust in deep-space interplanetary medium are not precise [7, 8]. But the amount of gas is much less that the amount of dust.[3] The amount of dust is believed to be relatively high. Further, most of the dust should be in orbit about the Sun, so the drag velocity will effectively be the radial velocity of the craft.

The final result will also depend on $\mathcal{K}_{\mathtt{d}}$, which means it depends on the sizes of the particles and especially on the properties of the sail. A determination of what should be used for $\mathcal{K}_{\mathtt{d}}\rho(r)$ is in practice very difficult. There is a complicated distribution of dust

[3] The gas is believed to come mainly from the interstellar medium as the Sun revolves around the galaxy [8]. Therefore, the drag of the gas is "unidirectional" in the sense that it has a velocity relative to the solar system of about 25 km/s. (Thus, the actual gas drag velocity on a spacecraft is the vector sum of the craft's velocity, $\approx$ 70 km/s, and this 25 km/s.) Its constant density is roughly equal to that of the solar wind at 20 AU, so about one hydrogen atom per 100 cm^3.

grains of various sizes. Symbolically, one can write

$$\mathcal{K}_{\mathtt{d}}\rho(r) = \int_0^\infty \mathcal{K}_{\mathtt{d}}(m)\ \rho(r,m)\ dm. \tag{8}$$

For now we just leave it as a constant.

Therefore, with the spacecraft properties we are using, and taking the value for $v_s(r)$ to be 67.5 km/s, as given by Eq. (6), we find

$$a_{\mathtt{d}}(r) = -1.91 \times 10^{-3}\ \mathcal{K}_{\mathtt{d}}\ \left[\frac{\rho(r)}{10^{-20}\ \mathrm{g/cm}^3}\right]\ \mathrm{cm/s}^2. \tag{9}$$

Since a solar sail would be rotationally stabilized, there would be little use of attitude-control jetting. In fact, the sails would be "trimmed" (pulled in and out) to affect attitude. Therefore, the precision of the navigation could approach that of a true spinner. This means that with Doppler and range navigation techniques, as well as the occasional use of Very Long Baseline Interferometry (VLBI) with the differenced Doppler (ΔDOR) technique, modern yet off the shelf X-band tracking could be precise to less than 10^{-9} cm/s^2 over a year [10].

Further, the forces of Sec. 2 all vary as $1/r^2$. Given an almost constant velocity, the drag force varies roughly as the density of the medium. This makes it even easier to distinguish a drag force.

Therefore, even with possible heat systematics , with proper craft design [10] a density of 1 hydrogen atom cm^{-3} should easily be seen. A measurement of the drag force would provide information on what might be the content of $\rho(r,m)$ [7]. Given that test experiments on the sail material are done to determine what $\mathcal{K}_{\mathtt{d}}$ is for the interplanetary medium, such a measurement could be an independent confirmation to the results from any particular ion, gas, and dust detectors on the craft.

This measurement could be done for r both less than and also greater than 5 AU (if the sail were retained for a longer period). If there were no overriding reason to get rid of the sail at 5 AU, we propose it be kept until at least past 30 AU, to reach the Kuiper

belt.[4] which would only be about 2 years more of mission time. The amount of new information obtained with each year would be very valuable.

After the sail is abandoned, the mission would be free to perform its primary objectives unencumbered, be they those of the InterStellar Probe mission [1]-[4] and/or any other objective.[5]

4 Discussion

Our Solar system is the end product of the common astrophysical process of stellar system formation from a protoplanetary disk nebula. Collisions play a central role in the formation and evolution of planetary systems, either increasing or eroding the mass of the bodies. The present interplanetary dust in the solar system is a result of such collisional processes. A deep space mission will provide an opportunity for both in situ and remote sensing (via infixed emission) of both interplanetary and interstellar dust in the heliosphere and in the interstellar medium.

A deep space mission can also determine the mass, composition, and orbital distributions of dust in the outer solar system,to aid in the study of its creation and destruction mechanisms. It can also search for dust structures associated with planets, asteroids, comets, and the Kuiper belt.

These studies will constrain theories of collisional dynamics in the solar system and help us understand the origin and nature of our solar system, not to mention other planetary systems. Finally, a deep space mission can uniquely give insight into the fundamental question of the radial extent of the primordial solar nebula and, more precisely, the extent of the primordial planetesimal disk.

Some time ago, Boss and Peale had derived a model for a non-uniform density distribution in the form of an infinitesimally thin disc extending from 30 AU to 100 AU in

[4] The Southwest Research Institute in Boulder maintains a bibliography of articles on the Kuiper belt [9].

[5] An example would be a test [10, 11] of the Pioneer anomaly [12, 13].

the ecliptic plane [16]. More recent infrared observations have ruled out more than 0.3 Earth mass of Kuiper Belt dust in the trans-Neptunian region [7, 17, 18].

More recently, two primary mass concentrations at 39.4 AU and 47.8 AU, corresponding to Neptune upon Pluto resonances of 3:2 and 2:1 [14, 15] were discovered. For a different reason, to obtain a limit on gravitational forces, three specific mass distributions were also studied including this distribution [13], namely: i) a uniform distribution, ii) a 2:1 resonance distribution with a peak at 47.8 AU, and iii) a 3:2 resonance distribution with a peak at 39.4 AU.[6]

One can combine the results of Refs. [7, 13] to determine an upper limit on the drag acceleration acting on a sail by Kuiper belt dust. The drag acceleration would be on the order of 10^{-5} cm/s^2. This and the other effects given above could easily be observed, if the sail were retained into quite deep space,

Further, these accelerations would not be constant across the data range. Rather, they would show an increasing effect as the spacecraft approached into the belt and a decreasing effect as it receded from the belt, even with a uniform density model in the belt. This behavior makes the detection of the Kuiper belt dust contents with a solar sail a reasonably easy task, which justifies the use of the solar sail for this objective.

We emphasize that *if* a deep-space solar-sail mission flies then, with modest forethought and planning, the illuminative additional information on the matter content of the solar disk could easily be obtained. This course of action must be seriously considered.

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[6] A total mass of one Earth mass was assumed, which is significantly larger than the standard estimates given above.

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